

# Supernova classes and subclasses

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## Abstract.

The discovery of many objects with unprecedented, amazing observational characteristics caused the last decade to be the most prolific period for the supernova research. Many of these new supernovae are transitional objects between existing classes, others well enter within the defined classes, but still show unique properties. This makes the traditional classification scheme inadequate to take into account the overall SN variety and, consequently, requires the introduction of new subclasses.

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## INTRODUCTION

After the appearance of SN 1987A, whose anniversary we are celebrating, the number of discovered of Supernovae (SNe) has literally exploded [1, *see <http://web.pd.astro.it/supern/snean.txt>*]. The improved monitoring capabilities, quality of the observations and extension of the spectral range has produced an unexpected diversification of the observed properties and, as a consequence, the proliferation of SN types and subtypes among which only the most experienced specialists are able to extricate themselves.

The final aim of the SN classification is the arrangement of these vast arrays of objects into categories according to basic physical parameters such as initial mass of the progenitor, explosion mechanism, stellar population, metallicity, etc. To this aim all kinds of information should be used including, in addition to the conventional data on the SN (spectroscopy, photometry, polarimetry), also information on the parent population (locations inside the parent galaxy, stellar population at the site of explosion, pre-explosion observations and circumstellar environment) as well as particle flux (neutrinos, cosmic rays).

Usually a *quick and dirty* SN classification (typing) based on the presence/absence of spectral features is obtained as soon as possible after the discovery in the framework of *ad hoc* projects on small/medium class telescopes which make use of their flexible scheduling to accommodate Target of Opportunity observations. This quick classification, required to point out the most interesting targets for subsequent intensive observational campaigns, usually hold extensive studies. On the other hand there are well studied objects whose physical nature is debated also after long-standing campaigns, e.g. SN 2002ic (cfr. next Sections).

High redshifts SNe are nowadays discovered on-demand by patrolling large volumes of Universe with wide-field imagers mounted on large telescopes. Their faintness prevents extensive studies on individual objects and the type assignment for all candidates. In the wake of wide-field spectroscopic multiplexer on large telescopes [e.g. 2], statistical methods have been developed which make use of the SED distribution derived from the photometry to type the SN candidates with a reasonable probability [3].

Aim of this review is to update the general classification scheme of SNe on the basis of the latest results also discussing the most recent objects challenging the consolidated scenario. Detailed classification schemes for SNe can be found in [4, 5, 6, 7].

## THE CONSOLIDATED SCENARIO

It is widely accepted that SNe result from two major explosion mechanisms, the gravitational collapse of the stellar nucleus (core collapse) and the thermonuclear runaway. The core collapse takes place in massive stars ( $M \geq 8M_{\odot}$ ) at the end of a series central nuclear burnings which end up with the formation of an iron core, and results in the formation of a compact remnant, a neutron star (NS) or a black hole (BH). The different configurations of the progenitors at the moment of the explosion, the different energetics associated to the event and the possible interaction of the ejecta with circumstellar material (CSM) produce a large variety of displays.

The thermonuclear disruption of CO White Dwarfs (WDs), which have reached the Chandrasekhar mass limit accreting matter from a companion in binary systems, produces those we normally call type Ia Supernovae (SNIa). Whether the donor is another degenerate star or a main sequence/red giant star is still debated, as well as whether the burning front propagates as a subsonic deflagration or turns into a detonation, in the so-called delayed-detonation models [8]. Recent 3-D deflagration models seem to fail in representing true SNIa explosions, both because the low energy released in this kind of explosion and the full mixing between fuel and ashes not seen in SNIa spectra [9].

## TYPE IA SUPERNOVAE

The CO WD scenario well explains the main observational properties of these objects such as the lack of H lines, the occurrence in all type of galaxies and their overall similarity. Nevertheless in the nineties a new paradigm for SNe Ia was developed. Intrinsic differences were identified in the luminosities at maximum which correlate with the early light curve shape, brighter objects having broader light curves than dimmer ones [10, 11, 12, 13, 14]. This sequence was matched by spectroscopic variations attributed to changes in the effective temperatures, which, in the context of Chandrasekhar-mass explosions, were interpreted as variations in the mass of  $^{56}\text{Ni}$  produced in the explosions [15]. These correlations have been employed in restoring SNIa as useful distance indicators up to cosmological distances but do not fully account for the entire dispersion/diversity observed [e.g. 16].

The Chandrasekhar mass scenario has been recently challenged by SN 2003fg, a bright (2.2 times more luminous than normal) SNIa with usual spectral features and

relatively low expansion velocity. SN 2003fg did not obey the empirical relations between the light curve shape and the luminosity at maximum and therefore objects like this, though intrinsically very rare in the local Universe, may contaminate the searches of high- $z$  SNIa for cosmology. The progenitor was estimated to be  $2.1 M_{\odot}$  (i.e. **Super-Chandra**) [17, 18] which in principle might form by the merge of two massive WDs. However also the possible interpretation with a Chandrasekhar mass model has recently been proposed [19].

Based on the analysis of the photometric and spectroscopic properties of a sample of 26 objects Benetti et al. [20] have identified three subclasses of SNIa with distinct physical properties, the main characterizing parameter being the gradient of expansion velocity of the photosphere. **Faint** SNIa (similar to SN 1991bg) are fast decliners both in luminosity and expansion velocity, have typically low expansion velocities and occur in early-type galaxies. High- (HVG) and low-velocity (LVG) gradient SNIa include normal objects, although the LVG group also includes all the brightest, slow declining SNe (like SN 1991T). Even if the statistical analysis suggests that LVG and HVG are two distinct groups, they may possibly represent a continuum of properties. More peculiar objects, like SNe 2000cx [21] and 2002cx [22, 23] were not included in the above analysis.

In a recent work Mazzali et al. [24] have performed a systematic spectral analysis of a large sample of well observed type Ia SNe (including SN 2000cx). Mapping the velocity distribution of the main products of nuclear burning, they tried to constrain the theoretical scenarios behind the SNIa phenomena. They found that all supernovae have low-velocity cores of stable Fe-group elements, while outside radioactive  $^{56}\text{Ni}$  dominates the supernova ejecta. The outer extent of the iron-group material depends, thus, on the amount of  $^{56}\text{Ni}$  and coincides with the inner extent of Si, the principal product of incomplete burning. Surprisingly, they found that the outer extent of the bulk of Si is similar in all SNe ( $\sim 11000 \text{ km s}^{-1}$ ) corresponding to a mass slightly over  $1M_{\odot}$ . This indicates that all considered SNe burned a similar amount of material, and this suggests that their progenitors had the same initial mass. Synthetic light curve parameters and three-dimensional explosion simulations support this interpretation. A single explosion scenario, possibly a delayed detonation, may thus explain most SNIa. What then drives the main explosion outputs (e.g. luminosity) is the strength of the central deflagration and the extent of star burned before the detonation goes off. The remaining diversity among SNIa could then be explained by 3-D effects present in the outer part of the envelopes like ejection of blobs of burned material along the line of sight and interaction with the CSM. These phenomena are also responsible for the high velocity features (HVF) seen in early spectra [25].

## TYPE IA SUPERNOVAE AND CSM

In the past years many attempts aimed to identify the progenitor systems of SNIa have been carried out, some of them focused on the detection and possible characterization of the CSM. The radiation arising from the interaction between the fast moving SN ejecta and the slow moving CSM in the form of narrow optical emission lines has been searched for [26, 27], as well as radio [28] and X-ray emission [29].

Radio observations provide very stringent limits which in a few cases are as low as  $3 \times 10^{-8} \text{ M}_{\odot} \text{ yr}^{-1}$  for an assumed wind velocity of  $10 \text{ km s}^{-1}$  [28]. Recently, the sub-luminous SN 2005ke has been tentatively detected in X-rays domain by mean of deep monitoring with the XRT onboard of Swift satellite. The inferred X-ray luminosity [ $L = (2 \pm 1) \times 10^{38} \text{ erg s}^{-1}$  in the 0.3–2 keV band] has been interpreted as the interaction of the SN ejecta with circumstellar material deposited by a stellar wind from the progenitor’s companion star having a mass-loss rate of  $3 \times 10^{-6} \text{ M}_{\odot} \text{ yr}^{-1}$  [29].

A more robust detection of CSM around SNIa has been obtained using high resolution spectroscopy. Repeated observations of the interstellar/circumstellar NaID doublet in the normal type Ia SN 2006X have revealed short-scale time variations [30]. The expansion velocities, densities and dimensions of the CS envelope indicate that this material was ejected from the progenitor system short before the explosion (50 years). Among others clues, the relatively low expansion velocities ( $\sim 50 \text{ km s}^{-1}$ ) favor a progenitor system where, at the time of the explosion, the WD is accreting material from a non-degenerate (probably a red-giant star) companion. Moreover, the amount of CS material deduced (a few  $10^{-4} \text{ M}_{\odot}$ ) is compatible with the radio non-detection of normal SNIa.

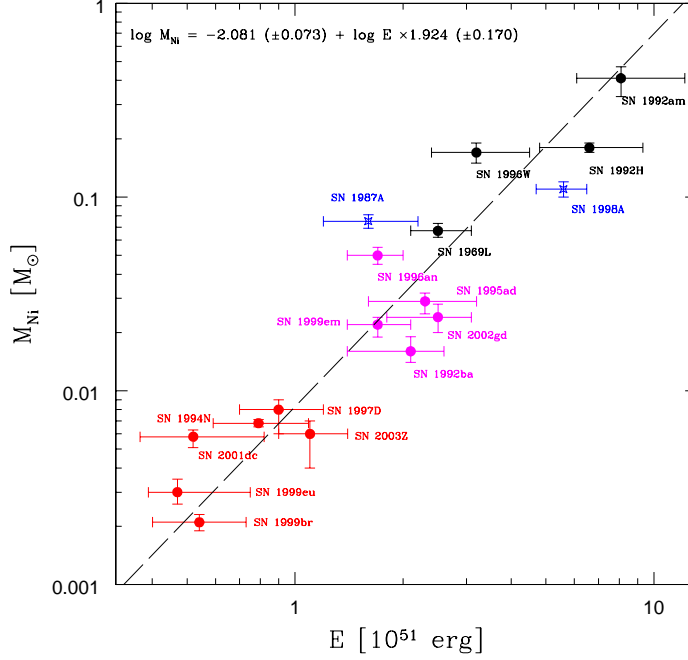
In the context of evanescent CSM around SNIa two remarkable exceptions are represented by SNe 2002ic and 2005gj, which have shown pronounced H emission lines [31, 32] that have been interpreted as a sign of extremely strong ejecta-CSM interaction. It must be noted, however, that their classification as interacting type Ia SNe has been recently been questioned by Benetti et al. [33], who suggested that SN 2002ic (and SN 2005gj [34]) actually were type Ic SNe, i.e. that their progenitors were massive. In this scenario the observed interaction with dense circumstellar material is the predictable consequence of the intense mass-loss activity of the progenitor. Because of the striking similarity of the late-time spectra with those of SNe 1997cy and 1999E, SN 2002ic establishes a link between energetic SNIc and the highly interacting SNIIn, and add some credit to the proposed association of these SNIIn to GRBs [35, 36, 37, 38].

If the scenario proposed for SNe 2002ic and 2005gj is correct, the detection of CSM in SN 2006X [30] remains the only certain signature of CSM around the progenitor system of a SNIa.

## TYPE II SUPERNOVAE

Type II SNe represent core-collapse explosions occurring in progenitor stars still retaining the H envelopes. They span large ranges in the observables like luminosity at maximum, explosion energy, ejected Ni mass, etc. [4, 39]. Three major classes are often considered, type II Plateau SNe (**SNIIP** [40]) with flat light curves in the first few months, type II Linear SNe(**SNIIL** [40]) with rapid, steady decline in the same period, and the narrow-lined SNII (**SNIIn** [41]), dominated by emission lines with narrow components, sign of energetic interaction between the SN ejecta and the CSM. Numerous intermediate objects among SN classes exist as well as a large variety within each individual class. Several attempts have been made to sort out more physical classification schemes although none of them has proved to be fully satisfactory [e.g. 42].

SNIIP have been the subject of extensive analysis by Hamuy [43] who pointed out a continuum in the properties of these objects and revealed several relations linking the



**FIGURE 1.** Ejected  $^{56}\text{Ni}$  mass vs. explosion energy ( $E$ ) for a sample of SNIIP [from 44].

observables and the derived physical parameters, with more massive progenitors producing more energetic explosions. A similar, independent analysis [44] has been performed on a sample more extended toward the low- and high-luminosity objects, confirming the continuity in the physical properties over a very broad range. In particular, the group of **faint, slowly expanding** SNe with characteristics similar to SN 1997D [45, 46], which are explained by spherical explosions that undergo a large amount of fallback, appears as the low luminosity tail of the distribution of properties of SNIIP. SN 1987A and the somehow similar SN 1998A [47], having light curves with pronounced secondary maxima at about 3 months after the explosion, are two outliers in the SNIIP family. In Fig. 1 is shown the  $^{56}\text{Ni}$  mass as a function of the explosion energy. These quantities correlates very well over two orders of magnitudes in  $M_{\text{Ni}}$  and one in  $E$ .

The existence of **ultrafaint** (still undetected) core-collapse SNe, even fainter than SN 1997D, has been suggested in the framework of GRBs. Indeed there are at least two examples of nearby, long-duration GRBs, for which no optical counterpart brighter than  $M_V = -13.5$  has been identified [48, 49, 50]. Tominaga et al. [51] have shown that faint (and ultrafaint), low-energy SNe with little  $^{56}\text{Ni}$  ejection are compatible with relativistic jet-induced BH-forming explosions of massive stars.

## TYPE IB/C SUPERNOVAE

The core-collapse of massive stars which have lost their H (and He) envelopes before the explosion produces SNIb (SNIc). These objects have recently deserved large attention because of their relation to GRBs. Indeed long-duration GRBs at sufficiently close distance have been coupled to bright, highly energetic type Ic SNe.

SN 2003dh associated to GRB030329 [e.g. 52] and SN 2003lw/GRB031203 [e.g. 53] were similar to the first prototypical SN 1998bw/GRB980425 having broad-line SNIc features. Detailed analysis showed that these SNe require even more than  $10^{52}$  erg, somewhat less in case of asymmetric explosion, justifying the introduction of the term **hypernovae** [54]. They are believed to be the outcome of very energetic black hole forming explosions of massive stars ( $30\text{--}50 M_{\odot}$ ) which synthesize large amounts of  $^{56}\text{Ni}$  ( $0.3\text{--}0.5 M_{\odot}$ ). In addition to the above mentioned cases, there are a number of **broad-line SNIc** for which an accompanying GRB has not been detected, e.g. SNe 1997ef [e.g. 55], 2002ap [56], 2003jd [57]. These SNe have a tendency to have smaller luminosity, mass of the ejecta and explosion energy than GRB-SNe but it is not clear whether the non-detection of the GRB is a geometric effect due to asymmetries or an intrinsic property of the explosion.

The soft, nearby GRB060218, classified as an X-Ray Flash (XRF), was associated to another SNIc, 2006aj, which was less bright than GRB-SNe and whose spectral lines were not as broad [58]. The spectral and light curve modeling indicate that the mass of the ejecta is smaller ( $2 M_{\odot}$ ), the amount of  $^{56}\text{Ni}$  still considerable ( $0.2 M_{\odot}$ ), and the explosion energy only marginally larger than the canonical  $10^{51}$  erg. According to Nomoto et al. [59] the considerable variety in the broad-line SNIc (associated to GRBs, XRF or not associated) may be explained in a unified scenario with jet-induced explosions.

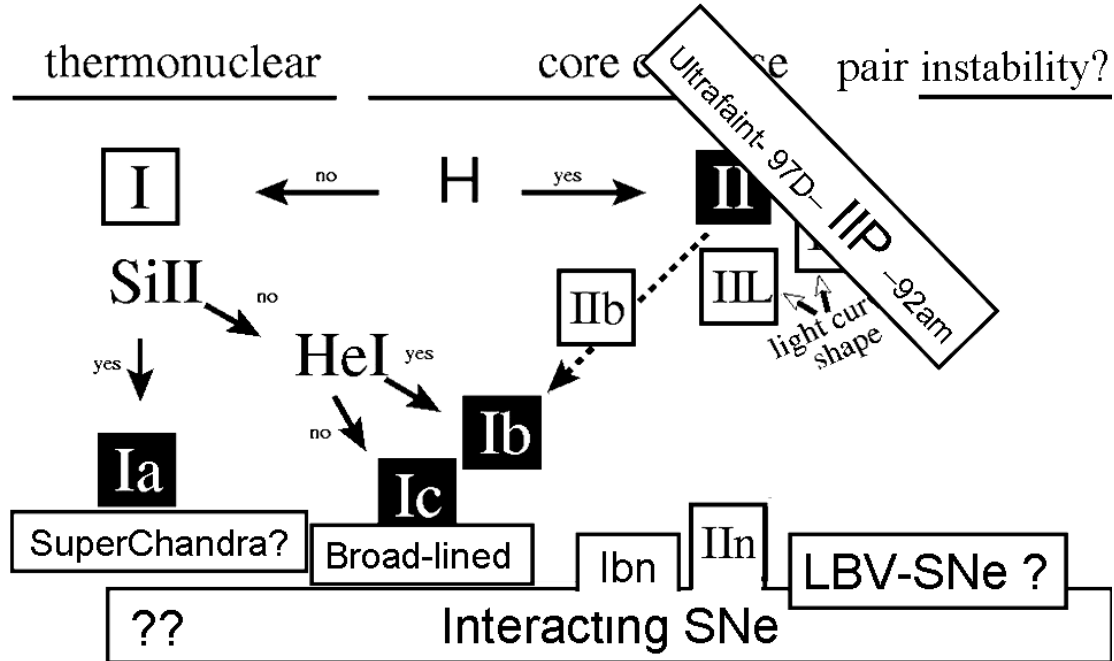
## SUPERNOVAE FROM EXTREMELY MASSIVE PROGENITORS

In the last months, before the beginning of this conference, two remarkable SNe have occurred which might shed light on the final fate of extremely massive stars.

SN 2006gy was discovered close to the nucleus of the parent galaxy. For this reason it was early debated if it was actually a SNIIn [60] or an AGN [61]. Further observations proved that it was a SN with unique characteristics: very slow rise to maximum (about 70d) and decline, coupled to an extremely bright luminosity,  $M_{V,max} \sim -22$  [62, 63]. These make the total radiated energy larger than  $10^{51}$  erg, which can be explained only with the explosion of a very massive stars either if the light curve is powered by CSM interaction or by radioactive decay of  $^{56}\text{Ni}$  [63]. The presence of several solar masses of unshocked circumstellar gas expanding at  $130\text{--}260 \text{ km s}^{-1}$  is inconsistent with masses of the progenitor smaller than  $40 M_{\odot}$ . Therefore Smith et al. [63] have suggested that it was the explosion of a LBV star, like  $\eta$  Carinae, with an initial mass as large as  $100\text{--}150 M_{\odot}$ , which failed to shed its entire H envelope before the explosion and did not become a WR star.

The explosion mechanism invoked would, then, be the pair-instability collapse, for which theoretical light curves have been presented [64]. Indeed pair-production SNe

# Taxonomy 2007



**FIGURE 2.** The 2007 version of the classification scheme of SNe. It should be considered as an updated version of Figure 1 of Turatto [7].

are expected to produce very broad light curves with bright maxima, to have spectra showing H lines with expansion velocity of the order of  $5000 \text{ km s}^{-1}$ , and to synthesize up to several tens of solar mass of  $^{56}\text{Ni}$ . Although these models have been computed only for non-rotating stars of zero metallicity, the pair-production SNe hypothesis is certainly an intriguing scenario. If confirmed, this unique SN might reveal that some very massive stars do not collapse directly onto a BH but explode with a bright display with obvious consequences on the possible detection of Population III SNe.

Shortly after SN 2006gy another object, SN 2006jc, appeared with optical display very different but still astonishing. The spectrum was that of an H-poor event with broad SNIc features, much narrower He emissions and very blue continuum [65, 66]. For this reason it has been proposed [65] that it should be more properly classified as a **type Ibn** SN. The narrow He I spectral emissions together with the presence of a strong X-ray emission were evidences of interaction between the ejecta of an CO Wolf-Rayet star with a dense He-rich CSM. Despite these peculiarities, the most interesting property of SN 2006jc is that it was spatially coincident with a bright ( $M_R = -14.1$ ) optical transient detected in 2004 [65]. Similar outbursts characterize LBVs, massive stars showing significant optical variability due to unstable H-rich atmospheres and episodic mass loss. Current evolutionary theories do not predict the core collapse during the LBV phase

but statistical arguments strongly disfavour the random spatial coincidence of these two events. It appears therefore that we have testified in 2004 a sort of LBV-like eruption of an WR, which subsequently exploded as SN 2006jc [65, 66].

## CONCLUSIONS

The current classification scheme of SNe is an evolving tool scientists have developed to sort out groups of objects physically related. Despite the long record of SNe discovered and studied so far [67, and on-line updates] the taxonomy of SNe is far from being steadily defined and understood. Not only we are still discovering new common properties and differences among the objects of consolidated types, but also we are still identifying new classes which are opening new unexpected scenarios on the final fate of stars. In Fig. 2 we report an updated version of the SN taxonomy published in Turatto [7] to the light of the most recent findings discussed above.

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